Technical Challenges to Systems Analysis and MDAO for Advanced Subsonic Transport Aircraft

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Subsonic Fixed Wing Project

SFW Strategic Thrusts & Technical Challenges

Energy Efficiency Thrust *(with emphasis on N+3)*
Develop economically practical approaches to improve aircraft efficiency

Environmental Compatibility Thrust *(with emphasis on N+3)*
Develop economically practical approaches to minimize environmental impact

Cross-Cutting Challenge *(pervasive across generations)*

Energy & Environment

2011 NASA Strategic Plan

National Aeronautics Research and Development Plan February 2010

TC1 - Reduce aircraft drag with minimal impact on weight (aerodynamic efficiency)

Drag

TC2 - Reduce aircraft operating empty weight with minimal impact on drag (structural efficiency)

Weight

TC3 - Reduce thrust-specific energy consumption while minimizing cross-disciplinary impacts (propulsion efficiency)

TSEC

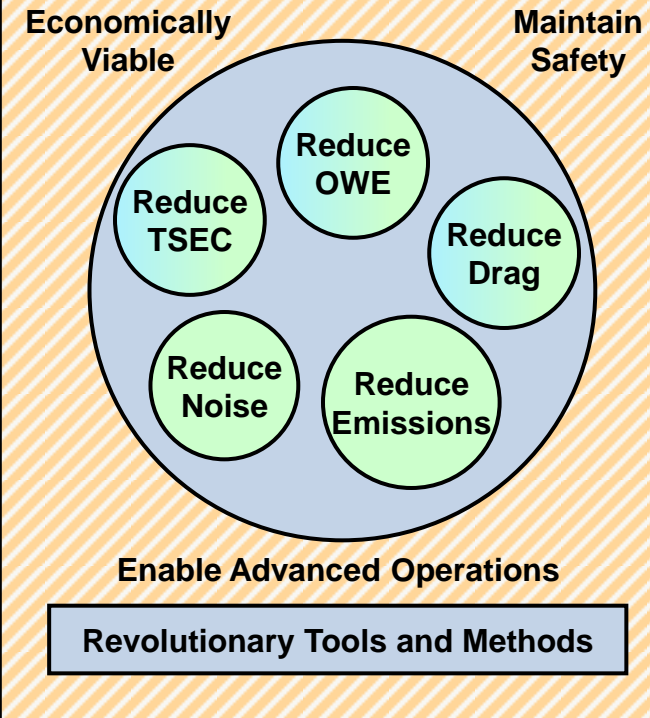**TC4 - Reduce harmful emissions** attributable to aircraft energy consumption

Clean

TC5 - Reduce perceived community noise attributable to aircraft with minimal impact on weight and performance

Noise

TC6 - Revolutionary tools and methods enabling practical design, analysis, optimization, & validation of technology solutions for vehicle system energy efficiency & environmental compatibility

Tools

Economically Viable

Maintain Safety

Reduce OWE
Reduce TSEC
Reduce Drag
Reduce Noise
Reduce Emissions

Enable Advanced Operations

Revolutionary Tools and Methods

☐ - Direct Impact

┆ - Indirect Impact

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

*   Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

**   ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used
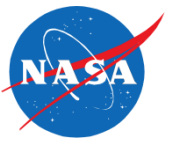
FAA/CLEEN ➡ **NASA/ERA** ➡ **NASA SFW**

Diversified Portfolio Addressing N+3 Goals
broadly applicable subsystems and enabling technologies

N+3 Vehicle Concepts

N+3 Subsystem Concepts

Tailored Fuselage	High AR Elastic Wing	Quiet, Simplified High-Lift	High Eff. Small Gas Generator	Hybrid Electric Propulsion	Propulsion Airframe Integration	Alternative Fuels

Technical Areas

Tailored Fuselage	High AR Elastic Wing	Quiet, Simplified High-Lift	High Eff. Small Gas Generator	Hybrid Electric Propulsion	Propulsion Airframe Integration	Alternative Fuels
Turbulent CF Drag Reduction	Aerodynamic Shaping	Active Flow Control	Hot Section Materials	Gas-Turbine/Electric Hybrids	Aerodynamic Configuration	Fuel Properties
Tailored Load Path Structure	Elastic Aircraft Flight Control	High-Lift System Noise	Tip/Endwall Aerodynamics	Transmission and Winding Materials	Adaptive, Lt Wt Fan Structure	Emission & Performance
Designer Materials	Tailored Load Path Structure	Landing Gear Noise	Decentralized Control	Aircraft Power Distribution	Distortion Tolerant Fan	
	Designer Materials		Fuel-Flexible Combustion		Acoustic Liners	
	Active Structural Control		Core Noise		Propulsion Airframe Aeroacoustics	

Legend:
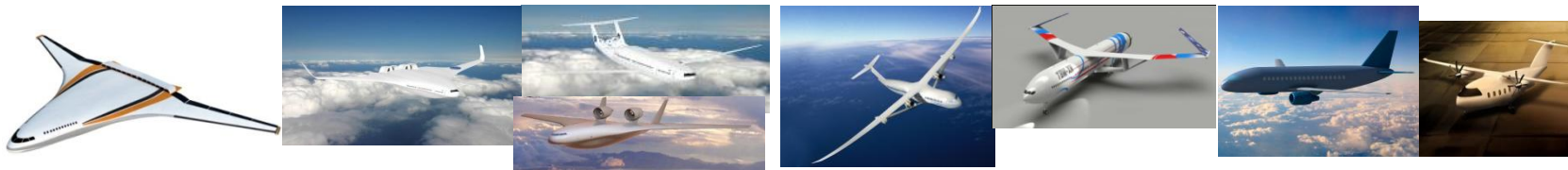- Drag
- Weight
- TSEC
- Clean
- Noise
- Tools

Tool Box – MDAO, System Modeling, Physics-Based Tools

Structure/Aero-elastic/Materials	Aerodynamics	Acoustics	Combustion	Propulsion	MDAO	Systems Analysis/ Conceptual Design

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N+3 Vehicle Concepts

N+3 Subsystem Concepts

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Vehicle/Propulsion Assessments

SA&I Primary Focus Areas

Enhanced Tools & Methods

Drag

Weight

TSEC

Clean

Noise

Tools

Tool Box – MDAO, System Modeling, Physics-Based Tools

Structure/Aero-elastic/Materials	Aerodynamics	Acoustics	Combustion	Propulsion	MDAO	Systems Analysis/ Conceptual Design

Envisioned Challenges – NASA Perspective

Systems Analysis/Conceptual Design Tools & Methods:

- Analyzing advanced/unconventional configurations using empirical-based prediction methods (conventional architectures)
- Limited/no uncertainty quantification
- Development of rapid turnaround, physics-based design/analysis tools
- Increased analysis efficiency – more accuracy with less time & effort
- Greater automation with intelligent streamlining of design process

MDAO Tools & Methods:

- Establishing standard interfaces between discipline tools
- Lack of mid-fidelity codes to bridge gap between low & high fidelity
- High computational costs for hi-fidelity tools limit number of function evaluations
- Optimization performance comparisons based on standardized test problem set
- Difficulty w/interfacing analysis environments to commercial CAD tools
- Common (tool independent) geometry interface to build analysis tools around
- Transition between multiple geometry engines as design process progresses

Moving Forward

- Over the past 6-9 months, SFW has identified technical challenges and then developed a strategic framework and tactical plans to guide project going forward

- In support of the project's objectives, Systems Analysis & Integration (SA&I) has several responsibilities:

  – Lead MDAO engineering framework development efforts

  – Develop new/enhanced conceptual design tools & methods

  – Conduct SFW's technology assessments

- Therefore, the sub-project structure consists of 3 critical elements

  – MDAO Tools & Methods

  – Systems Analysis/Conceptual Design Tools & Methods

  – Advanced Concepts: Modeling, Studies & Assessments

MDAO Tools & Methods

Focus: Develop an advanced, open source MDAO framework enabling the integration of multi-fidelity, multi-disciplinary design and analysis tools

Technical Content:

Open Source Framework Development (OpenMDAO): Continue development of open-source, Python-based multi-disciplinary engineering framework leading to initial "full" release (V1.0)

Geometry Development: NRA-led activity focused on the development of a geometry handling capability within the OpenMDAO framework. (NRA participants – MIT & University of Michigan)

MDAO Evaluation/Test Problem Formulation: Exercise existing OpenMDAO integration capabilities through a series of aerospace related test problems, included herein will be combustion & structure related activities

GEN2 MDAO Framework Validation: Validation of ModelCenter-based framework by assessing predictive capability of integrated set of design/analysis tools on state-of-the-art commercial transport (B787)
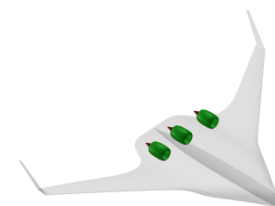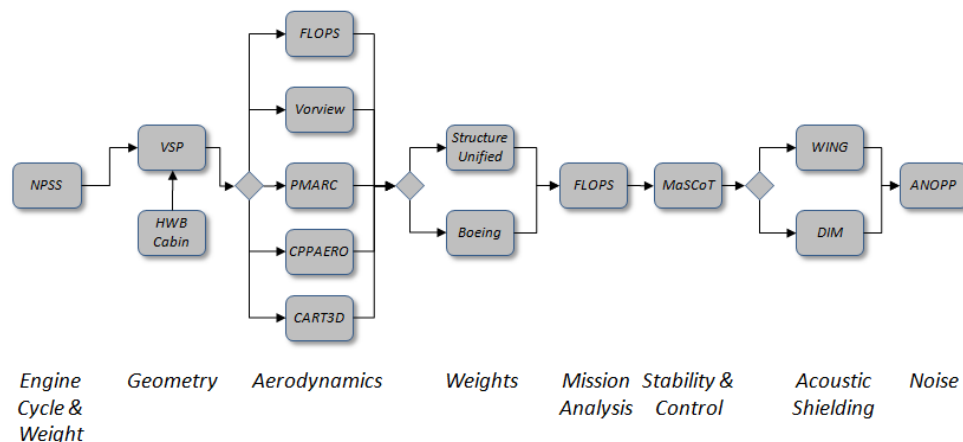
GEN2 MDAO Tool Suite Validation

- 2nd generation capability developed primarily to analyze unconventional systems
- Validation completed by comparing aircraft weight/performance for both configurations against independent data sources
- Predicted values met, or nearly met, accuracy targets for all metrics for both architectures

Conventional
B737-800
w/CFM56-7B26 engine

Unconventional
BWB-710
w/advanced 3-shaft engine

GEN2 MDAO Tool Suite - HWB

| Engine Cycle & Weight | Geometry | Aerodynamics | Weights | Mission Analysis | Stability & Control | Acoustic Shielding | Noise |

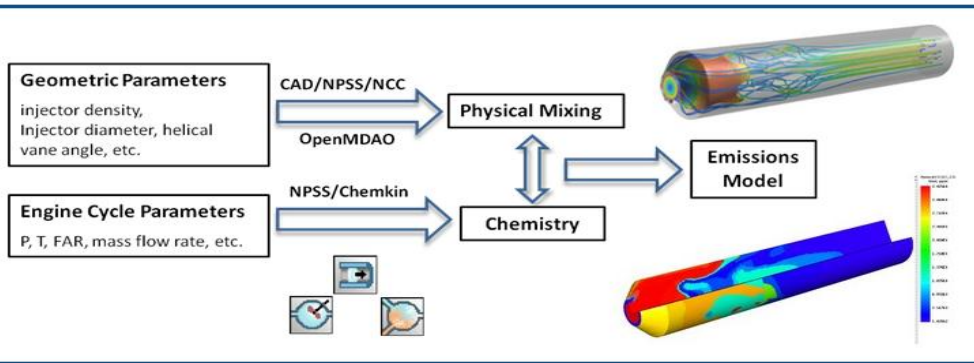| Metric	Conventional		Unconventional	
	% Diff	**Goal**	**% Diff**	**Goal**
Takeoff Gross Weight	-3.1%	± 5%	+2.0%	± 15%
Range	-0.1%	± 2.5%	-1.2%	± 10%
Takeoff Field Length	-4.2%	± 5%	+7.1%	± 15%
Landing Field Length	+2.3%	± 5%	+10.7%	± 15%
LTO NOx	-5.8%	± 5%	No Validation Data	± 15%
Avg EPNL	+2.1 dB	± 2.5 dB	No Validation Data	± 7.5 dB

Comparison of Prediction vs. Available Data

Sample of MDAO Tools & Methods Work (2)

OpenMDAO Application Problem – Lean Direct Injection Combustor

- Develop parametric-CAD approach for LDI combustor design
- Quantify influence of key aerothermodynamic variables on individual & coupled injector performance
- Investigate parametric-CAD approach to Hi-Fidelity (CFD) design-by-analysis addressing issues of geometry handling, automated meshing and Low/Hi-fidelity code coupling

Flow Diagram of Envisioned Process

Geometry Handling

Systems Analysis/Conceptual Design Tools & Methods
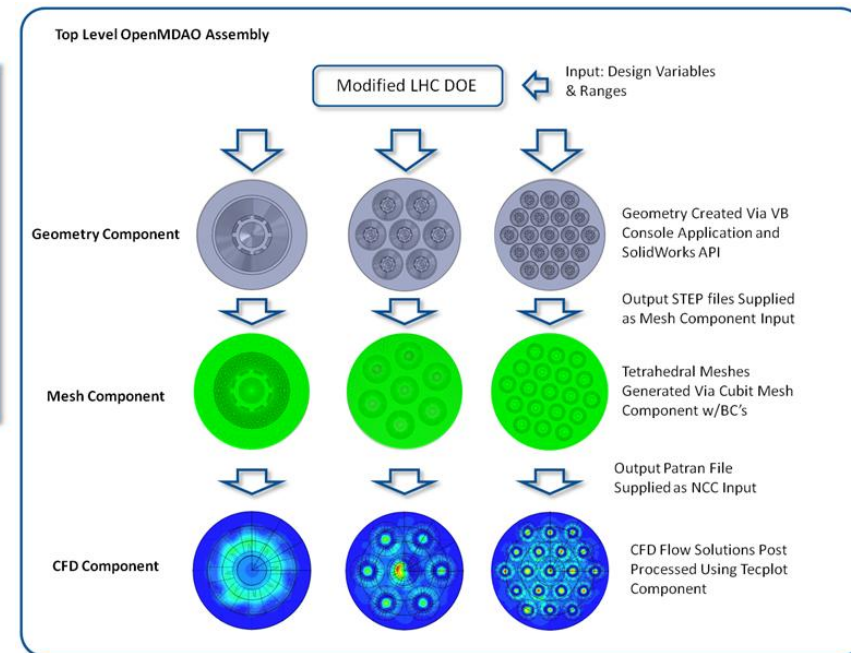
Focus: Develop higher order design and analysis methods that enable reliable and robust exploration of conventional and unconventional concepts

Technical Content:

Robust Parametric Geometry Tools: Develop robust parametric geometry tools to achieve the best conceptual design capability and foster/improve the geometric tools internally to insure functionality to maximize tool effectiveness. (NRA participants – Cal Poly-SLO & Georgia Tech)

Physics-Based Aerodynamic Design: Develop physics-based laminar flow/drag prediction tool that can be used in conceptual design process; investigate use of higher-order analysis methods to enable high-lift prediction tools suitable for system analysis/conceptual design.

Weight Prediction Enhancements: Develop process to bridge gap between conflicting requirements for quick concept development/evaluation and need for design detail to support high-fidelity analysis enabling integration of higher fidelity structural analysis into the conceptual design environment.

Physics-Based Aeromechanical Design: Enhance current engine flowpath/weight estimation tool (WATE++) by creating new modules that will represent some of components envisioned for N+3 (e.g., turbo-electric).

High-Fidelity MDAO for Highly Integrated Propulsion/Airframe: Develop quantitatively reliable/computationally efficient high-fidelity MDAO predictive capability for next generations of highly integrated propulsion & airframe configurations.

Sample of Systems Analysis Tools & Methods Work

High Fidelity MDAO for Highly Integrated Propulsion/Airframe

- CFD simulation of the HWB configuration with embedded engines (N2B)
- Provide aerodynamic characteristics of the complete configuration assessing the impact on propulsion system performance (incl. Boundary Layer Ingestion)
- Design optimization for
  - ✓ BLI inlet distortion/total pressure recovery
  - ✓ Integrated airframe-nacelle configuration

Outboard Inlet/Engines   Center Inlet/Engines

Distortion Visualization

Flow Streamlines
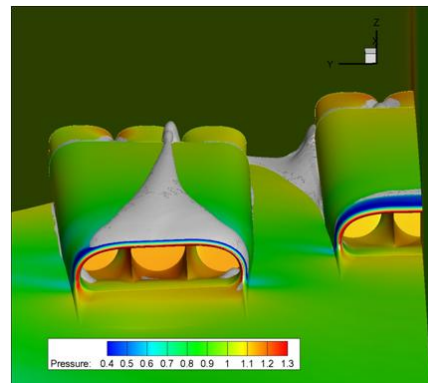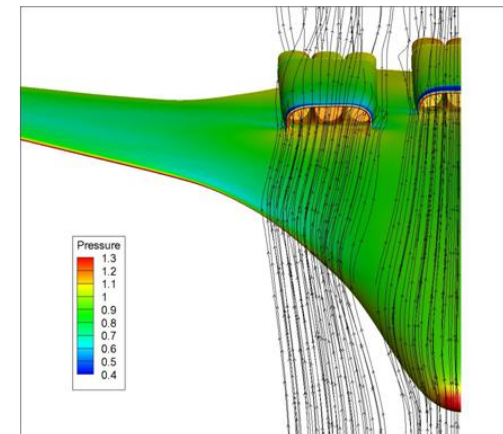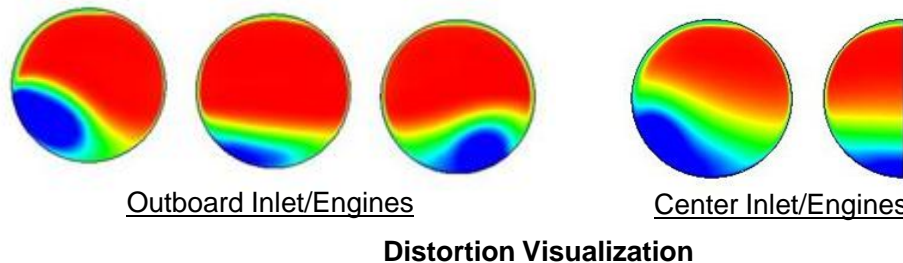
Flow Separation Visualization

Advanced Concepts

Focus: Model/assess advanced propulsion and airframe technologies to advance knowledge and understanding of a diverse collection of airliner concepts that move beyond the conventional vehicles of today

Technical Content:

SUGAR Phase II NRA Collaboration: Work in concert with NRA partners (Boeing, GE Aviation, VA Tech & GA Tech) to understand/independently assess N+4 reference and advanced technology concepts. In addition, provide an independent assessment of N+3 refined Truss-Braced Wing concepts and hybrid electric concepts.

Turbo-electric Distributed Propulsion: Enhance NASA's Turbo-electric Distributed Propulsion concept (N3-X) through further refinement of current in-house models to increase confidence of fuel burn reduction potential; in addition, perform acoustic and NO_X emission assessments.
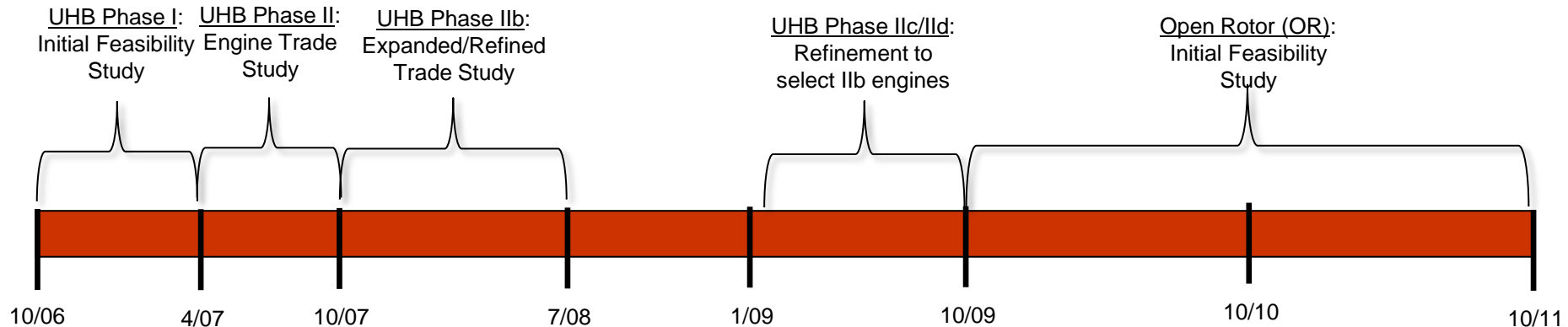
Open Rotor Integration Study: Enhance current open rotor assessment through high-fidelity modeling capability to improve understanding of installation effects on open rotor performance.

Conceptual Assessment of Pressure Gain Combustion: Perform conceptual level assessment of the potential benefits, and technology challenges, of pressure gain combustion for commercial transport engines.

Advanced Concept Work – Open Rotor

- SFW has been conducting an on-going engine trade study to assess propulsion options for advanced single-aisle (737/A320 class) aircraft

  – Initial focus on ultra-high bypass ratio (UHB) turbofan concepts, followed by investigation of open-rotor engine architectures

  – Multiple interactions with industry over the years to obtain feedback

  – Numerous technical reports and conference papers produced, plus 1 journal article

UHB Phase I: Initial Feasibility Study

UHB Phase II: Engine Trade Study

UHB Phase IIb: Expanded/Refined Trade Study

UHB Phase IIc/IId: Refinement to select IIb engines

Open Rotor (OR): Initial Feasibility Study

10/06 4/07 10/07 7/08 1/09 10/09 10/10 10/11

- Recently completed assessment of open rotor concept

  - Collaborative effort (w/GE) utilizing modern blade set performance/aero

  - Initial comparison of fuel burn/noise delta vs. geared turbofan

  - Technical report/conference paper detailing results planned for 2012

~9% Fuel Burn

N+1 Tech
UHB TF
BPR ~14

N+1 Tech
Open Rotor
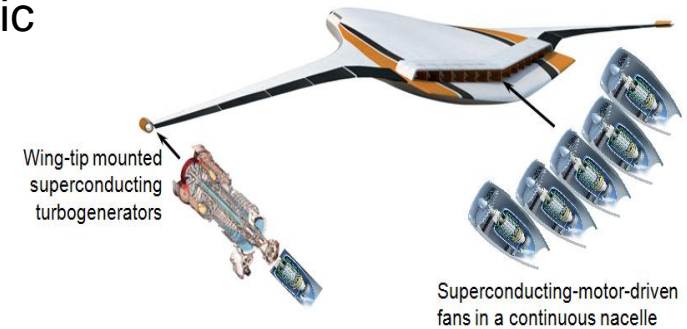BPR >30

~12 dB

Noise Margin

Baseline airplane:
"stretched, aero updated" MD90-30
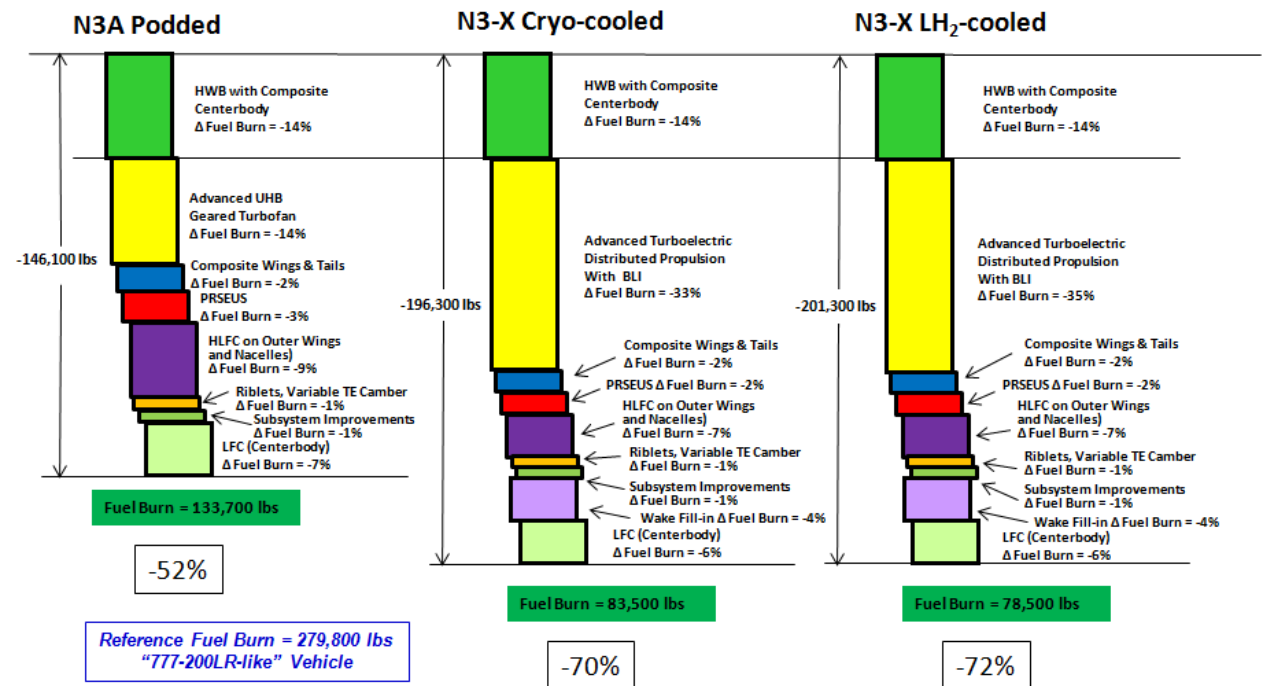
% Fuel Burn Benefit
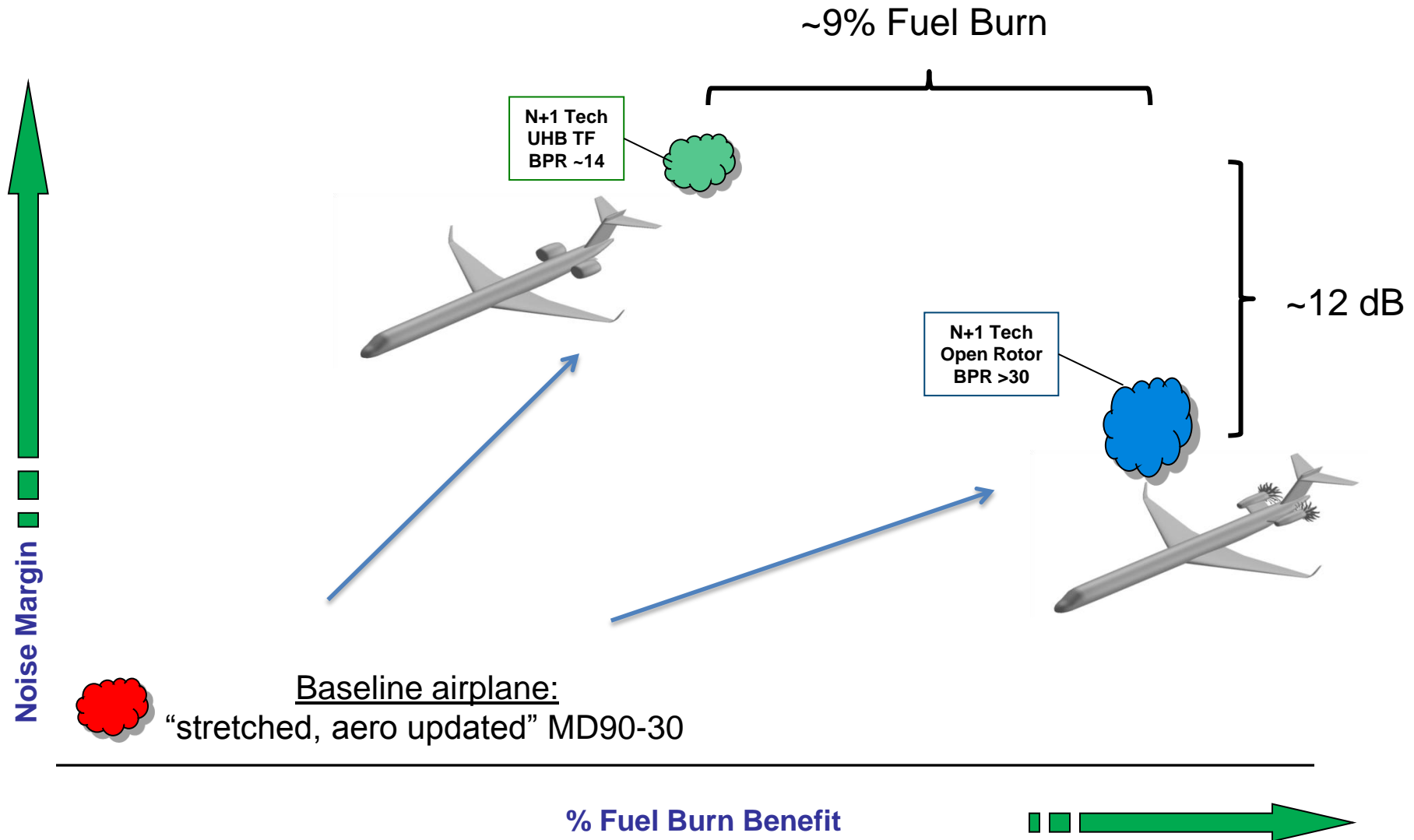
Advanced Concept Work – TeDP

- Study conducted to compare potential of turbo-electric distributed propulsion (TeDP) on HWB architecture
- Variants created (LH$_2$-cooled & podded TF) for comparison
- Preliminary fuel burn estimates tentatively meet N+3 goal but warrants further detail design analysis
- Next step involves investigation of concept's acoustic & emission potential


Wing-tip mounted superconducting turbogenerators

Superconducting-motor-driven fans in a continuous nacelle

TeDP Engine/Propulsor Description

N3A Podded

HWB with Composite Centerbody
Δ Fuel Burn = -14%

Advanced UHB Geared Turbofan
Δ Fuel Burn = -14%

Composite Wings & Tails
Δ Fuel Burn = -2%
PRSEUS
Δ Fuel Burn = -3%

HLFC on Outer Wings and Nacelles)
Δ Fuel Burn = -9%

Riblets, Variable TE Camber
Δ Fuel Burn = -1%
Subsystem Improvements
Δ Fuel Burn = -1%
LFC (Centerbody)
Δ Fuel Burn = -7%

-146,100 lbs

Fuel Burn = 133,700 lbs

-52%

Reference Fuel Burn = 279,800 lbs "777-200LR-like" Vehicle

N3-X Cryo-cooled

HWB with Composite Centerbody
Δ Fuel Burn = -14%

Advanced Turboelectric Distributed Propulsion With BLI
Δ Fuel Burn = -33%

Composite Wings & Tails
Δ Fuel Burn = -2%
PRSEUS Δ Fuel Burn = -2%
HLFC on Outer Wings and Nacelles)
Δ Fuel Burn = -7%
Riblets, Variable TE Camber
Δ Fuel Burn = -1%
Subsystem Improvements
Δ Fuel Burn = -1%
Wake Fill-in Δ Fuel Burn = -4%
LFC (Centerbody)
Δ Fuel Burn = -6%

-196,300 lbs

Fuel Burn = 83,500 lbs

-70%

N3-X LH$_2$-cooled

HWB with Composite Centerbody
Δ Fuel Burn = -14%

Advanced Turboelectric Distributed Propulsion With BLI
Δ Fuel Burn = -35%

Composite Wings & Tails
Δ Fuel Burn = -2%
PRSEUS Δ Fuel Burn = -2%
HLFC on Outer Wings and Nacelles)
Δ Fuel Burn = -7%
Riblets, Variable TE Camber
Δ Fuel Burn = -1%
Subsystem Improvements
Δ Fuel Burn = -1%
Wake Fill-in Δ Fuel Burn = -4%
LFC (Centerbody)
Δ Fuel Burn = -6%

-201,300 lbs

Fuel Burn = 78,500 lbs

-72%

Summary

- SFW has identified technical challenges and developed strategic framework and tactical plans to guide project going forward

- The project has created a diversified portfolio of technologies, with focus primarily (but not exclusively) in the N+3 timeframe

- Systems Analysis & Integration (SA&I) support centered in 3 areas:
  - MDAO engineering framework development effort
  - Systems Analysis/Conceptual Design Tool & Methods Development
  - Vehicle/Propulsion Assessments

- The sub-project is divided into 3 elements to address work:
  - MDAO Tools & Methods
  - Systems Analysis/Conceptual Design Tools & Methods
  - Advanced Concepts: Modeling, Studies & Assessments

- Requisite work defined to address technical challenges

- Several examples of recent accomplishments detailed
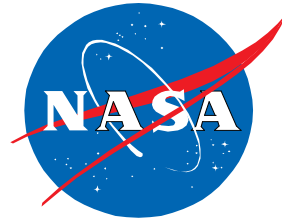
Rationale for Working Tools & Methods Development

What are we trying to do?
- Improve the ability to assess the performance, environmental compatibility, and risk of conventional and unconventional aircraft configurations and advanced technologies

Why?
- Lack of robust, reliable capability to accurately design/assess unconventional technologies/concepts is an obstacle to revolutionary changes in current design paradigms
- NASA needs ability to be an honest broker regarding the claimed advantages of unconventional configurations and advanced technologies
- Better tools will foster greater creativity and innovation in aircraft design

How is it done today, and what are the limits of current practice?
- Use of lower order methods limits ability to accurately model new configurations/technologies
- Successful use of higher order methods requires details not normally available in early design phases
- Proprietary COTS MDAO frameworks make it difficult for outside developers to integrate new capabilities directly into architecture

What is new in our approach?
- Interjection of more physics into conceptual design process with focus on bridging the gap between high order *analysis* and high order *design* capabilities
- Open source framework using Python programming language, enabling new tools to be constructed natively in framework
- Open source licensing enables collaboration across MDAO community

What are the payoffs if successful?
- Broad opportunities for contributions from external MDAO researchers and greatly expanded capability for MDAO users
- Ability to investigate new, innovative concepts with higher degree of confidence
- Better informed decisions regarding investment in unconventional concepts and technologies